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Anatomy of the brachial plexus (Plexus brachialis) and innervation of the thoracic limb of the Caracal (*Caracal caracal*)

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Abstract

This paper was focused on the anatomy of the brachial plexus of the caracal (*Caracal caracal*). This study identified the characteristics of this species and determined its similarity to other representatives of the Felidae. During the study, have recognized the following nerves: brachiocephalic (*n. brachiocephalicus*), suprascapular (*n. suprascapularis*), subscapular (*n. subscapularis*), axillary (*n. axillaris*), cranial pectoral (*n. pectorales craniales*), caudal pectoral (*n. pectorales caudales*), lateral thoracic (*n. thoracicus lateralis*), long thoracic (*n. thoracicus longus*), thoracodorsal (*n. thoracodorsalis*), radial (*n. radialis*), median (*n. medianus*) and ulnar (*n. ulnaris*). The formation of the plexus, the number and course of the identified nerves are important for comparative and clinical reasons. The plexus of the Caracal was constructed from branches C6-T1, which is characteristic of this group of animals. The information from this description may also be of use in work on anesthesiology. Veterinarians treating wild and zoo animals will benefit from a detailed knowledge of this study.

Running title: The brachial plexus of the Caracal

Keywords: nerves, roots, ventral branch, Felidae

Abbreviations: C5 – ventral branch of C5, C6 – ventral branch of C6, C7 – ventral branch of C7, C8 – ventral branch of C8, T1 – ventral branch of T1, T2 – ventral branch of T2, T3 – ventral branch of T3

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Introduction

The caracal (*Caracal caracal)* is a representative of the feline family (Felidae) found mainly in the southeastern part of the globe. It is also a species often found in zoos and is becoming an increasingly common companion animal. The genus Caracal consists of three species: *Caracal caracal, Caracal nubicus and Caracal schmitzi*. The Caracal was previously classified by scientists in the genus Felis, but the current division into a separate genus Caracal better illustrates the differences between Caracals and Felis. The caracal is widely distributed in Asia (India, Pakistan, Afghanistan, Iran, Turkmenistan), in the Arabian Peninsula, and Africa. The caracal is well adapted to a carnivorous lifestyle. A large proportion of the caracal's diet consists of rodents, suggesting excellent locomotor abilities [1]due to varying evolutionary strategies, carnivores differ in their metabolism and energy requirements. Hence, comparisons of diet between carnivores would be more meaningful if the body size and energetics of the predators are considered. The diet of three small carnivores (jungle cat Felis chaus; caracal Caracal caracal; golden jackal Canis aureus. Indeed, despite caracals' much thinner muscle fibers and less diverse muscle fiber composition, compared to lions and humans, they can generate up to 3 times more power [2]. Furthermore, the caracal is characterized by relatively long thoracic limbs [3].

The present study was devoted to the structure of the brachial plexus (*Plexus brachialis*). The brachial plexus is the part of the nervous system responsible for the innervation of the muscles of the thoracic limb, the brachiocephalic muscles, and the pectoral region. In addition, it is an important structure for the sympathetic innervation of the thoracic limb, and the roots from which the brachial plexus arises are involved in the formation of the phrenic nerve (International Committee on Veterinary Gross Anatomical Nomenclature) [4]. The anatomy of the brachial plexus has been studied in many laboratory species [5–8], as well as in farmed and companion species [9,10]. Information on the characteristics of different groups of animals is of both comparative and clinical value. Descriptions focusing on the brachial plexus structure of Feliformia concentrate on the suborder Feloidea. Species described to the present include the: Eurasian lynx (*Lynx lynx*)

The aim of my study was to describe the brachial plexus *(Plexus brachialis*) of the caracal (*Caracal caracal)*.

Material and methods

The study was conducted on a female representative of the Caracal, obtained from the zoo. The study material was fixed in a 10% formaldehyde solution for 14 days. The study was based on the preparation of the thoracic limb and thorax using surgical instruments. Neural structures were visualised with 2% hydrogen peroxide [20]. Preparation began with the removal of skin from the entire thoracic area and thoracic limbs. Preparation began with the removal of skin from the entire thoracic area and thoracic limbs. The skin was also removed from the brachium and distal part of the thoracic limb. The sternal attachments of the pectoral muscles were then cut away so that a sagittal incision of the sternum could be made without damaging them. The organs filling the thoracic cavity were then removed along with the unnecessary surrounding connective tissue and blood vessels. The individual bellies were cleaned and, if possible, separated from each other to expose the course of the individual nerves. The images were taken with a camera (Nikon D3200). Names of anatomical structures were standardised according to Nomina Anatomica Veterinaria [4]. The use of the research materials followed the national law of 15 January 2015 (Law of 15 January 2015 about the protection of animals used for scientific or educational purposes (Dz. U. poz. 266)).

Results

The brachial plexus of the caracal consisted of C6-T1 (**Fig. 1**). At the level of C7 there was a branch connecting with the cervicothoracic ganglion. The C6 and C7 branch was involved in the formation of the phrenic nerve. The plexus was formed by three roots: cranial, medial, and caudal. It consisted of peripheral long branches and peripheral short branches. The short branches included the brachiocephalic (*n. brachiocephalicus*), suprascapular (*n. suprascapularis*), subscapular (*n. subscapularis*), axillary (*n. axillaris*), cranial pectoral (*n. pectorales craniales*), caudal pectoral (*n. pectorales caudales*), lateral thoracic (*n. thoracicus lateralis*), long thoracic (*n. thoracicus longus*) and thoracodorsal (*n. thoracodorsalis*). In turn, the long branches are the musculocutaneous (n. musculocutaneous), radial (*n. radialis*), median (*n. medianus*), and ulnar (*n. ulnaris*) nerves.

The radial nerve arising from C7-T1 formed the median trunk and contacted the axillary nerve. The first muscle branch innervated the m. tensor fasciae antebrachii. The second and also the largest muscle branch for the caput longum of the m. triceps brachii. The third branch innervated the caput mediale of the m. triceps brachii. Another innervated the accessory head. Then n. radilalis innervated caput laterale of the m. triceps brachii. A branch for

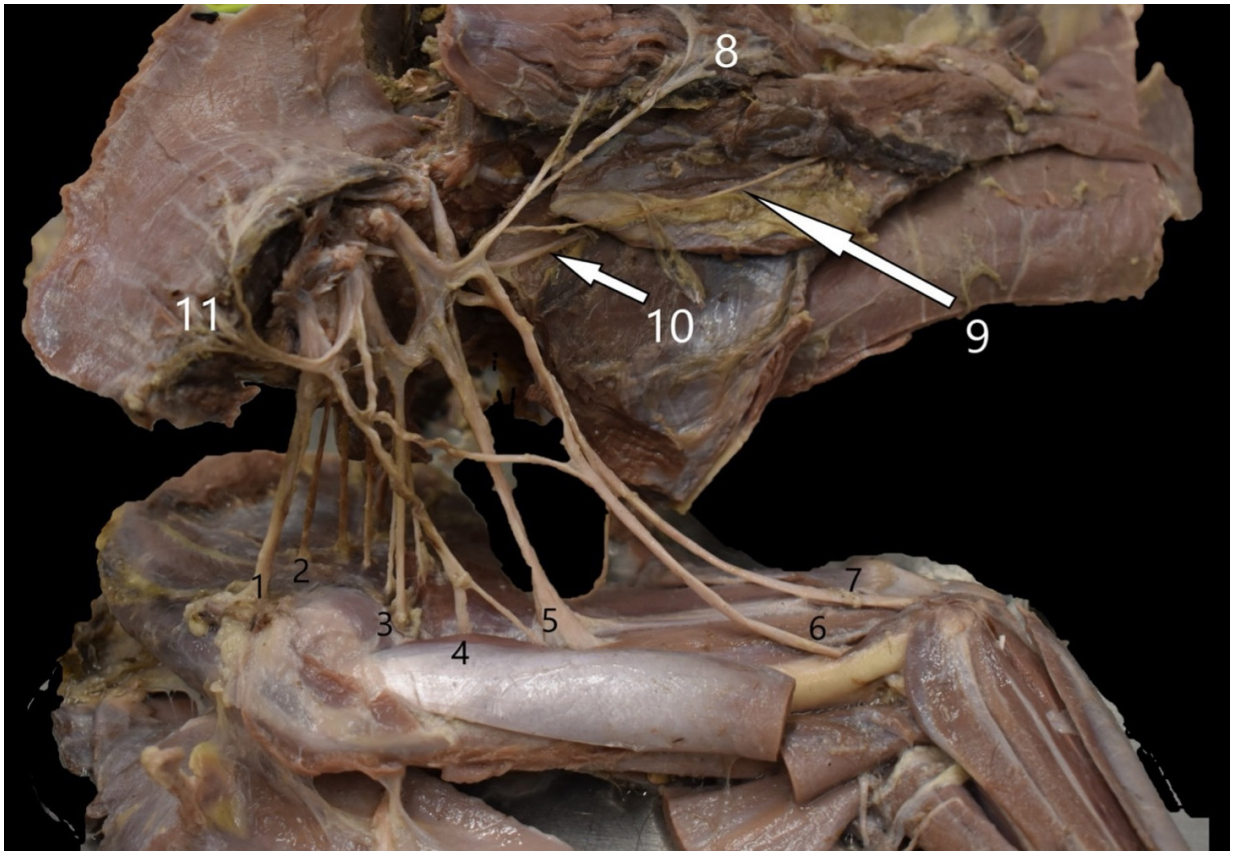

FIGURE 1 Anatomy of the right brachial plexus of the caracal. 1 – n. suprascapularis. 2 – nn. subscapularis. 3 – n. axillaris. 4 – n. musculocutaneus. 5 – n. radialis. 6 – n. medianus. 7 – n. ulnaris. 8 – nn. pectorales caudales. 9 – n. thoracicus lateralis. 10 – n. thoracicus longus. 11 – n. pectoralis cranialis

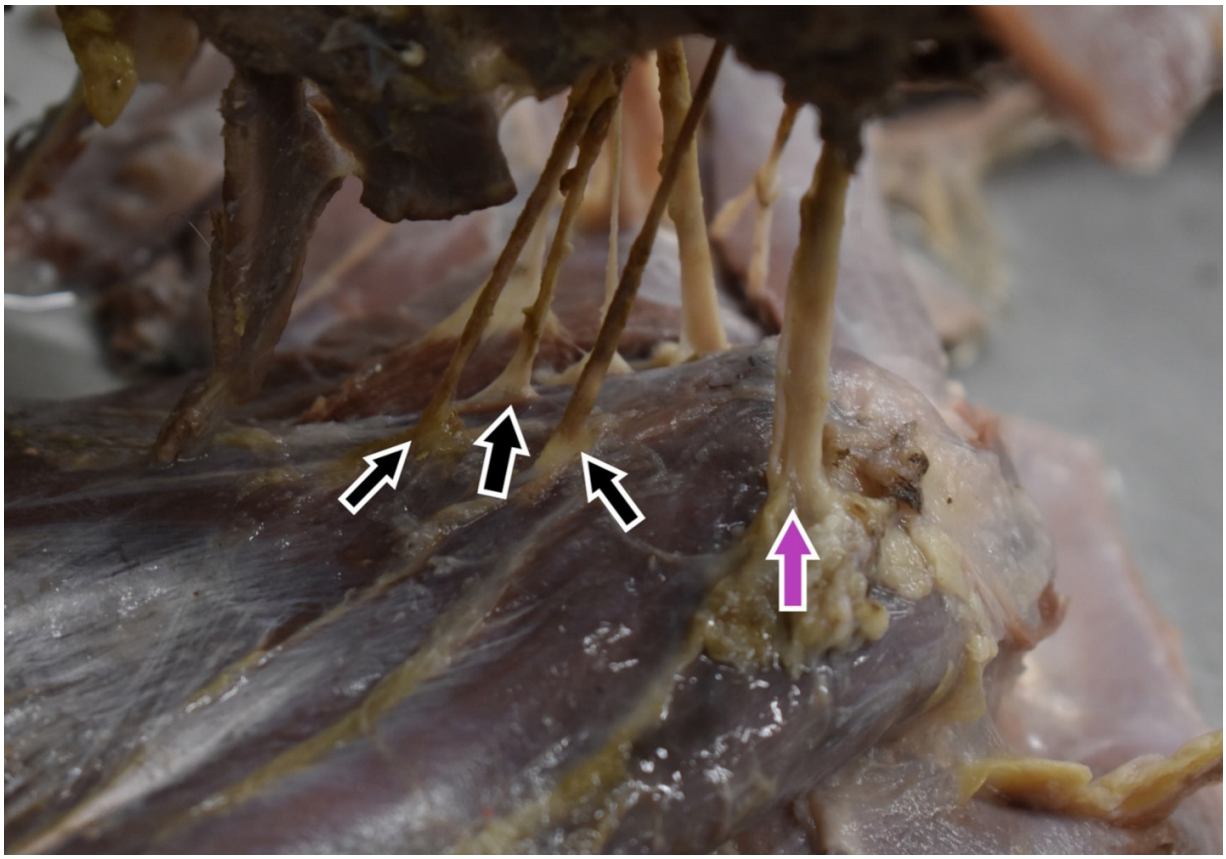

FIGURE 2 Innervation of the m. subscapularis of the caracal. Black arrow – nn. subscapulare, pink arrow – n. suprascapularis

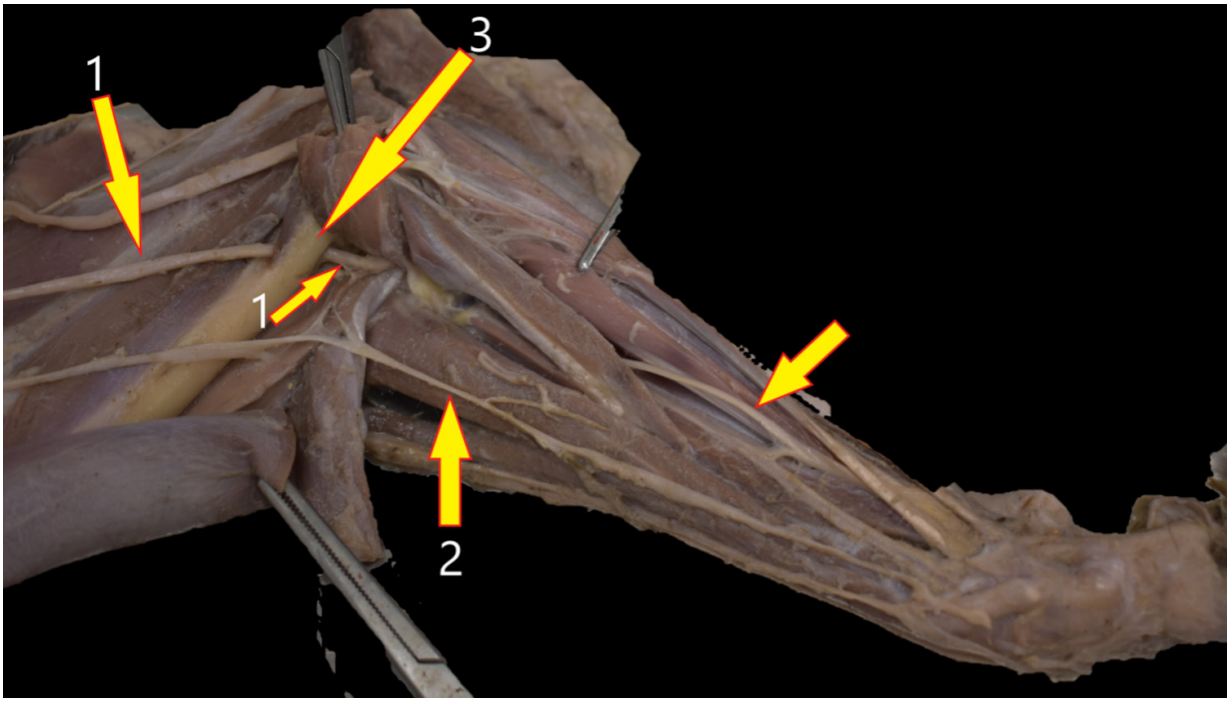

FIGURE 3 Course of the n. medianus and n. musculocutanus of the caracal. 1 – n. medianus. 2 – n. musculocutanues. 3 – entepicondylar foramen

the anconeus muscle detached immediately behind it. The last muscle branch at the level of the brachium was aimed for m. brachioradialis. Still at the level of the brachium, the *n. cutaneus brachii lateralis caudalis* and the *n. cutaneus antebrachii lateralis* were formed. The radial nerve was divided into a deep and a superficial branch. The fibres of the deep branch of the radial nerve spread between the extensor muscles. The superficial branch was directed together with the *vena cephalica*. At the level of the antebrachium, it is divided into a medial and a lateral branch. On the hand, the lateral branch is responsible for innervating the first and partly the second finger. It gives off the dorsal nerve of finger I odaxial and forms the common dorsal nerve of finger I, which divides into the dorsal nerve of finger II abaxial and the dorsal nerve of finger I axial. The innervation of the hand is completed through the lateral branch of the superficial branch of the radial nerve, forming the common dorsal nerves II, III and IV. These, in turn, are subdivided into the axial and abaxial nerves of the respective fingers.

The musculocutaneous nerve originated from C6-8. The fibres forming the musculocutaneous nerve, after passing through the area of the nerve trunks, contacted the median nerve via a connecting branch (*rammus communicans cum n. mediano*). The musculocutaneous nerve at the level of the brachium was responsible for innervating the m. coracobrachialis and the m. biceps brachii as a proximal muscular branch. This branch was short and lay close to the surface of the muscle. At the level of brachium close to the elbow joint, the musculocutaneous nerve innervates the m. brachialis. After passing the elbow joint, this nerve surrounds the distal part of the belly of the m. biceps brachii and goes over the elbow joint to become the *n. cutenaus antebrachiali medialis*. It is responsible for innervating the skin on the medial side of the antebrachium, wrist and hand.

The axillary nerve originated from C6-8. Fibers of this nerve follow the thoracodorsal nerve, however, the axillary nerve lays closer to the caudal edge of the scapula in the sulcus between the subscapularis and teres major muscles. Before entering between these two muscles, the axillary nerve gives off muscular branches to these two muscles. Passing to the lateral surface of the scapula, encircling the shoulder joint, the fibers of the axillary nerve spread into the m. deltoideus (pars scapularis, pars acromialis and clavicularis) and innervate the obturator minor muscle.

The suprascapular nerve formed from C6-C7 is another nerve responsible for innervating the scapular muscles. It ran to the cranial edge of the scapula, where it inserts between the scapula and the m. supraspinatus. In the supraspinatus fossa, it gives off a branch for the mentioned muscle. After passing next to the spine of the scapula, it was on the infraspinatus fossa, where it ended its course between the fibres of the m. infraspinatus.

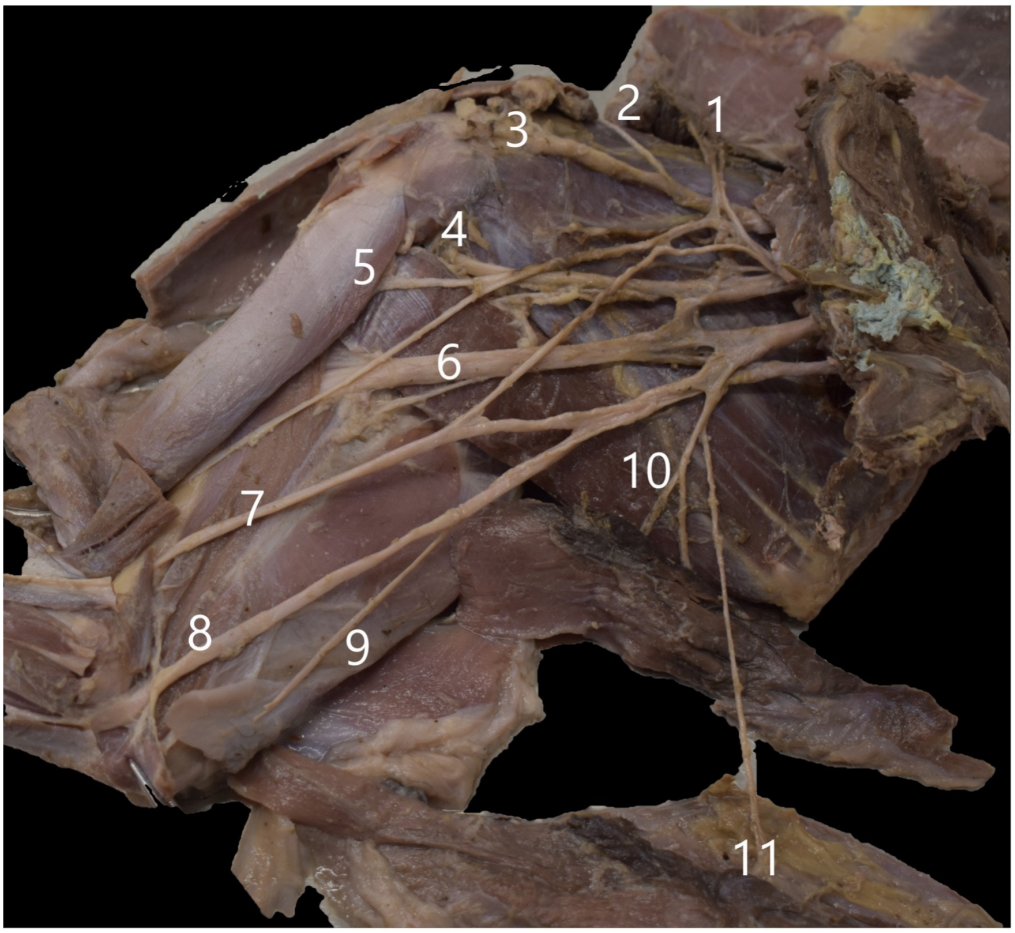

FIGURE 4 Anatomy of the right brachial plexus of the caracal. 1 – n. pectoralis cranialis. 2 – n. brachiocephalicus. 3 – n. suprascapularis. 4 – n. axillaris. 5 – n. musculocutaneus. 6 – n. radialis. 7 – n. medianus. 8 – n. ulnaris. 9 – n. cutaneus antebrachii caudalis. 10 – nn. pectorales caudales. 11 – n. thoracicus lateralis

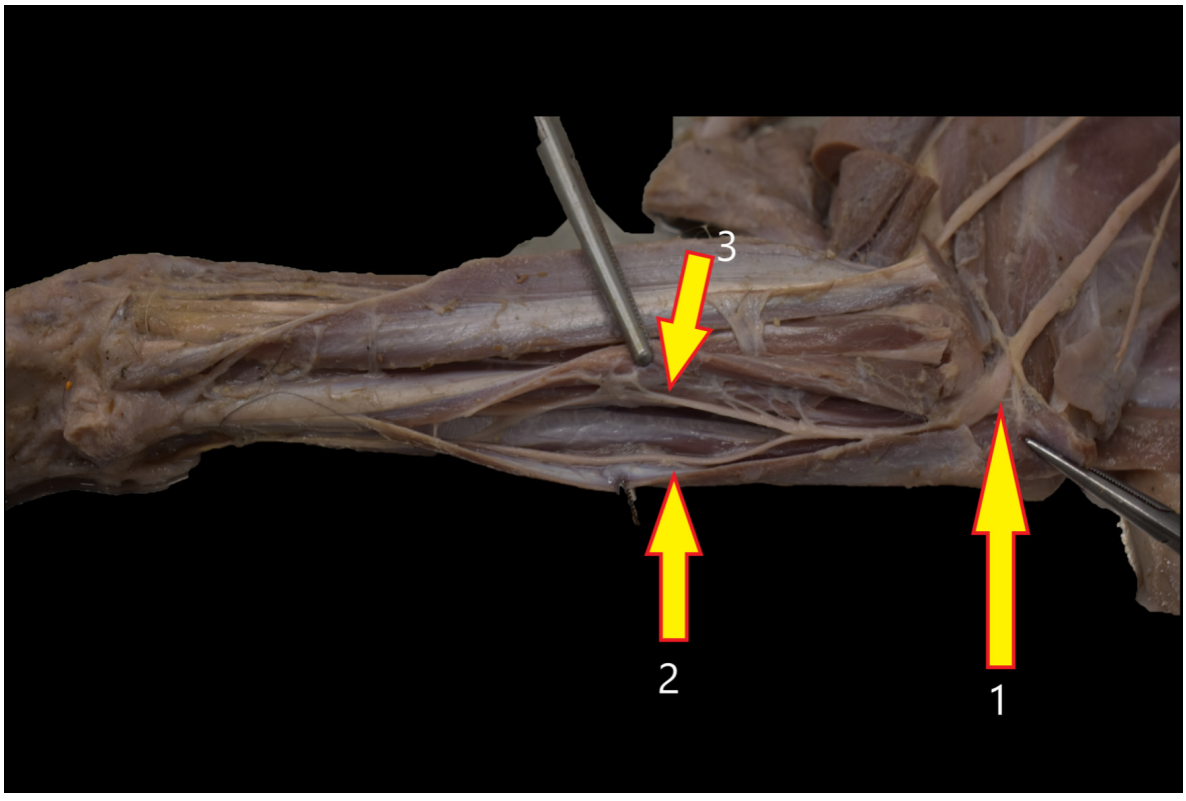

FIGURE 5 Course of the n. ulnaris on the antebrachium level in caracal. 1 – n. ulnaris. 2 – n. unlaris (ramus dorsalis). 3 – n. ulnaris (ramus dorsalis)

The subscapularis nerves consisted of C6-7. There were three nerves responsible for the innervation of the subscapularis muscle (**Fig. 2**).

The cranial pectoral nerve consisted of C6-C7 and was responsible for innervating the superficial pectoral muscles.

The caudal pectoral nerve consisted of C8-T1 and was responsible for innervating the deep pectoral muscle.

The thoracic long nerve consisted of C8-T1. It was formed from fibres that were not part of the nerve trunks – they detached before the trunks formed. It was responsible for the innervation of the m. serratus ventralis thoracis.

The lateral thoracic nerve consisted of C8-T1. It diverged close to the origin of the caudal thoracic nerves and together with them innervated the deep pectoral muscle. However, the largest part of the fibers ran to the m. cutaneus trunci.

The thoracodorsal nerve consisted of C7-8. It is responsible for innervating the m. latissimus dorsi.

The median nerve consisted of C7-T1. Together with the ulnar nerve, they form the caudal trunk. The median nerve connects to the musculocutaneous nerve with a strong connecting branch. The median nerve passes through the entepicondylar foramen together with the brachial artery and behind it gives a branch to the m. pronator trees and m. flexor carpi radialis (**Fig. 3**). It then innervates the m. flexor digitorum superficialis. The next branch is for the radial head of the m. flexor digitorum profundus and the m. pronator quadrates. The last muscular branch of the median nerve at the level of the antebrachium is intended to innervate the radial head of the deep flexor muscle of the fingers. After passing to the posterior surface of the antebrachium, it heads along the medial line of the thoracic limb. Behind the wrist, it divides into the N. digitalis palmaris communis I et II, and n. digitalis palmaris communis III.

The ulnar nerve consisted of C8-T1. Forms together with the median nerve the caudal trunk. It contacts the thoracic caudal nerves. The ulnar nerve gives off the *n. cutaneus antebrachii caudalis* (**Fig. 4**). Then the ulnar nerve, while passing at the elbow joint level, give off muscular branch to the m. epitrochleoanconeus.

Muscle branches at the level of the antebrachium provided innervation to the muscles: ulnar flexor of the wrist, ulnar head, and brachial head of the deep flexor of the fingers (**Fig. 5**). At the level of the wrist, it divides into a palmar and a dorsal branch. The palmar branch divides into a superficial branch, which first gives off the n. digitalis palmaris communis IV and then the N. digitalis palmaris V abaxialis. The deep branch of the palmar branch of the ulnar nerve forms the nn. metacarpei palmares. In the case of the dorsal branch of the ulnar nerve, it completes the innervation of the dorsal part of the hand at the level of the fifth finger on the odiaxial side forming n. digitalis dorsalis V abaxialis and co-forms n. digitalis dorsalis communis IV.

The brachiocephalic nerve formed from the C6 branch innervates the skin of the shoulder and neck. It formed close to the n. sprascapularis and took a similar direction to it. Eventually, n. brachiocephalic entered between the bellies of the brachiocephalic muscle and m. omotrasversarius to branch out as cutaneous branches on the surface near the shoulder joint and lateral surface of the neck.

Discussion

Anatomical variability is important during both clinical assessment and brachial plexus surgery [21]. Variation can lead to differences from the expected root distribution, as well as changes in motor innervation of the upper limb muscles. Furthermore, differences may even alter surgical approaches to the brachial plexus. In this work, we have shown that the caracal brachial plexus is composed of C6-T1 branches. As indicated in the literature, this is the typical extent of the brachial plexus for felids. The appearance of prefixed and postfixed brachial plexuses among cats is unique. Only in the Great Ocelot does the plexus have a range of C5-T1 [17], or in the domestic cat C6-T2 [14,15]. There is still a possibility in the domestic cat that the T2 branch may be part of the brachial plexus [15]. In contrast, in the others examined this range is C6-T1 (**Tab. 1**). Although cats are a distinct group of large carnivores with unique traits, they share characteristics with other taxa. One of these is the Canidae (Caniformia). For example, the number of branches that enter the Caniformia plexus overlaps with that of the caracal [20,22]. The C6-T1(T2) range, typical of cats, was also possessed by a representative of canids, the pampas fox (*Lycalopex gymnocercus*) [23]. Similar results were obtained for studies on the red fox (*Vulpes vulpes*) [20,24], the domestic marten (*Martes foina*) [22], the short-eared wolf (*Atelocynus microtis*) [25], and the crab-eating fox (*Cerdocyon thous*) [26]. Even for a group as disparate as the South American fur seals (*Arctocephalus australis*), the plexus range is between C6-T1 [27]. There is individual variation such as the attachment of the C5 branch in the species mentioned, but it is nevertheless worth pointing out this correlation. Among Mustelidae, whose members are representatives of the Caniformia, there are also species character-

TABLE 1 The extent of innervation of the individual nerves of the caracal

NERVE	MUSCLES INNERVATED
Radialis	m. tensor fasciae antebrachii, m. triceps brachii, m. brachioradialis, extensor carpi radialis, m. extensor digitorum communis, m. extensor digitorum lateralis, m. extensor carpi ulnaris, supinator, anconeus
Axillaris	m. subscapularis, m. teres major, m. teres minor, m. deltoideus (pars scapularis, acromialis, clavicularis)
Medianus	m. pronator teres, m. flexor carpi radialis, m. flexor digitorum profundus, m. pronator quadratus, m. flexor digitorum superficialis
Ulnaris	m. flexor carpi ulnaris, m. flexor digitorum profundus, m. epitrochleoanconeus,
Musculocutanues	m. coracobrachialis, m. biceps brachii, and m. brachialis, skin of the antebrachium
Suprascapularis	m. supraspinatus, m. infraspinatus
Subscapularis	m. subscapularis
Pectoralis cranialis	m. pectoralis superficialis
Pectorales caudales	m. pectoralis profundus
Thoracicus longus	m. serratus ventralis thoracis
Thoracicus lateralis	m. cutaneus trunci
Thoracodorsalis	m. latissimus dorsi
Brachiocephalicus	skin of the shoulder and neck

ised by the absence of the T1 branch, an example of such an animal is the *Nasua nasua* [28]. On the other hand, the number of nerve roots that are involved in the formation of the brachial plexus of rodents (Rodentia) is much greater compared to felids. An example is the research dedicated to the superfamily Muroidea where there are species with a plexus extending from C4 to T2 as in the case of the djungarian hamster (*Phodopus sungorus*) [29]this study analyses the structure of this part of the nervous system of this species. It is important to know the details of this structure not only for cognitive reasons, but also due to the increasing clinical significance of rodents, which are often used in scientific research. The study was conducted on 55 specimens. Like in humans, the brachial plexus of the Djungarian hamster has three trunks. The following individual nerves innervating the thoracic limb of the Djungarian hamster: the radial nerve, median nerve, ulnar nerve, musculocutaneous nerve, axillary nerve, suprascapular nerve, thoracodorsal nerve, cranial pectoral nerves, caudal pectoral nerve, lateral thoracic nerve, long thoracic nerve, and subscapular nerves. Similarly to other mammals of this order, the brachial plexus of the Djungarian hamster ranges widely (C5-T1. In the *Galea spixii*, the plexus can extend as far as T3, however, in this species the plexus began only from C6 [30]. Before nerve trunks are even formed, the roots contact the sympathetic trunk via the cervicothoracic ganglion and contribute to forming the n. phenicus [31–33]. The nerve roots in the caracal connect into three trunks, which is also a characteristic of some representatives of Canidae and rodents [22,27,34]. In the mole-rat plexus (*Spalax leucodon*), a single trunk is distinguished for the entire plexus, which is rare in the literature for the brachial plexus [7]. The djungarian hamster (*Phodopus sungorus*), red squirrel (*Sciurus vulgaris*), and rat (*Rattus rattus*) have three trunks [29,35,36] this study analyses the structure of this part of the nervous system of this species. It is important to know the details of this structure not only for cognitive reasons, but also due to the increasing clinical significance of rodents, which are often used in scientific research. The study was conducted on 55 specimens. Like in humans, the brachial plexus of the Djungarian hamster has three trunks. The following individual nerves innervating the thoracic limb of the Djungarian hamster: the radial nerve, median nerve, ulnar nerve, musculocutaneous nerve, axillary nerve, suprascapular nerve, thoracodorsal nerve, cranial pectoral nerves, caudal pectoral nerve, lateral thoracic nerve, long thoracic nerve, and subscapular nerves. Similarly to other mammals of this order, the brachial plexus of the Djungarian hamster ranges widely (C5-T1. The presence of three trunks in

TABLE 2 The range of nerve roots in the formation of the brachial plexus and peripheral nerves in different species

NERVE	DOMESTIC CAT [15]	VAN CAT [18]	ARGENTINE OCELOT [16]	GREAT OCELOT [17]	MOUTAIN LION [14]	CARACAL (OUR STUDY)	EURASIAN LYNX	SNOW LEOPARD [12]	JAGUARUNDI [13]
Radialis	C7-T1	C7-C8	C7-T1 C7-C8	C7-T1	C7-T1	C7-T1	C7-T1	C7-T1	C6-T1
Axillaris	C6-C7	C6-C7	C7 C6-C7	C7	C6-C7	C6-C7	C6-C7	C7-T1	C6-C8
Medianus	C8-T1	C7-T1	C7-T1 C7-C8	C7-T1	C7-T1	C7-T1	C7-T1	C7-T1	C7-T1
Ulnaris	C8-T1	C8-T1	C8-T1	C8-T1	C8-T1	C8-T1	C8-T1	C8-T1	C7-T1
Musculocutanues	C6-C7	C6-C7	C6-C7 C6 C7	C6-C7	C6-C7	C6-C7	C6-C7	C7	C6-C8
Suprascapularis	C6-C7	C6 C6-C7	C6 C5-C6	C6-C7	C6	C6-C7	C6-C7	C6	C6-C7
Subscapularis	C6-C7 C6-C8	C6-C7	C6-C7	C6-C7	C6-C7	C6-C7	C6-C7	C7-T1	C6-C7
Pectoralis cranialis	C6-T1 C7-T1	C7	C7-C8 C6-C7 C7	C6-C7	C7	C6-C7	C6-C7	C7	C6-C7
Pectoralis caudalis	C6-T1 C7-T1	C8-T1	C8-T1 C7-C8 C8	-	T1	C8-T1	C8-T1	C8-T1	C7-T1
Thoracicus longus	C7 C7-C8	C7	C7	-	C7	C7	C7	-	C6-C7
Thoracicus lateralis	C8-T1	C8-T1	C8-T1 C7-C8 C8	C8	T1	C8-T1	C8-T1	C8-T1	C7-T1
Thoracodrosalis	C7-C8	C7-C8 C8	C7-C8 C7	C8	C7-C8	C7-C8	C8-T1	C7-T1	C7-T1
Subclavius	-	-	-	C6-C7	-	-	-	-	-
Brachiocephalicus	-	-	C5 C6	-	-	C6	C6	-	C5-C6

a plexus is also characteristic of humans [37] and the normal position and/or morphological variations of the BP were determined and photographed.\nRESULTS: There were no variations in 93 plexuses, and 107 plexuses were observed to have different variations. Morphological variations were observed more frequently among female fetuses and right sides. The BPs were composed mostly of the C5, C6, C7, and C8 nerves and the T1 nerve (71.5%. Significant differences relate to the number of nerves present, and from which roots the nerves arise (**Tab. 2**). As a rule, the radial nerve and the median nerve appear to be the nerves with the widest range. It usually arises from three roots: two cervical roots, C7 and C8, and the first thoracic root. The most stable nerve in terms of which roots it arises from is the ulnar nerve, as in each species it arises from C8-T1 (**Tab. 2**). An equally uniform formation pattern can be indicated for the thoracodorsal nerve. Only in the great ocelot is it indicated that this nerve may arise only from the C8 root [17]. In contrast, the caudal pectoral nerves show the greatest variation. Considerable lability in the aforementioned nerves has been shown in the Argentine ocelot, in which there are as many as three root variants from which the caudal pectoral nerves can originate [16]. In turn, only in the great ocelot is this nerve absent however, the paper does not state which nerve has taken over the roles of innervating the deep pectoral muscles [17]. Furthermore, only in the great ocelot has the presence of the subclavian nerve been reported [17]. This may be related to the presence of a clavicle in the thoracic limb structure of the great ocelot [38]. In our species, no such nerve was distinguished, although a vestigial clavicle was present. However, the presence of a clavicle does not appear to be inextricably linked to the presence of a subclavian nerve [39]. This is indicated by work reporting the presence of this bony structure in the mountain lion, in which the subclavian nerve was not recorded [40]. An equally rarely recorded brachiocephalic nerve, the presence of which was demonstrated in our study, appears in the work on the Argentine ocelot, the Eurasian lynx, and in the puma jaguarundi

Conclusions

The anatomy of the brachial plexus of the caracal has characteristics specific to the group to which it belongs. The extent of the plexus, C6-T1, is standard for the aforementioned group and the distal architecture (trunk formation) follows the pattern that most mammals present. Morphologically, it appears to be most similar to the brachial plexus of the Eurasian lynx.

Ethical approval
The conducted research is not related to either human or animal use.

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Conflict of interest statement
The authors declare no conflict of interest.

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